HISTORY / HISTOIRE

A "brief" history of spectroscopy on EBIT[1]

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Abstract: In the autumn of 1986, the first electron beam ion trap, EBIT, was put into service as a light source for the spectroscopy of highly charged ions. On the occasion of the twentieth anniversary of EBIT, we review its early uses for spectroscopy, from the first measurements of X-rays from L-shell xenon ions in 1986 to its conversion to SuperEBIT in 1992 and rebirth as EBIT-I in 2001. Together with their sibling, EBIT-II, these machines have been used at Livermore to perform a multitude of seminal studies of the physics of highly charged ions.

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Résumé : À l'automne de 1986, le premier piège ionique à faisceau d'électrons, EBIT, entrait en service comme source de lumière pour la spectroscopie des ions fortement chargés. À l'occasion du vingtième anniversaire de EBIT, nous passons en revue ses premières utilisations en spectroscopie, des premiers rayons X de la couche L du xénon en 1986, jusqu'à sa conversion en super-EBIT en 1992 et la renaissance de EBIT-I en 2001. Avec leur frère, EBIT-II, ces instruments ont été utilisés à Livermore dans de multiples études qui ont marqué la physique des ions fortement chargés.

[Traduit par la Rédaction]

1. Introduction

Twenty years have passed since the first electron beam ion trap (EBIT) was put into operation. The EBIT has been an extraordinarily successful device, which has inspired seminal papers in multiple areas of atomic physics as well as in closely related fields crossing over to astrophysics, nuclear physics, plasma physics, high-energy physics, and material science. During the past twenty years several hundred papers have been published by the Livermore EBIT group — the compendium of EBIT papers compiled on the occasion of the twentieth anniversary of EBIT comprises about 3000 pages! Moreover, the number of similar devices has continued to increase over the years, and at present there are over a dozen such devices under construction or in operation.

In the following, we give a brief history of the development of EBIT as a spectroscopic light source and of the associated spectroscopic instrumentation. We point out some of the physics addressed with EBIT, and we conclude by mentioning some of the topics that may be studied in the future.

2. EBIT development

From its inception, EBIT was conceived as an X-ray source [1]. Summarized in one sentence, its goal was to produce X-ray spectra from basically any ion of any element on the periodic table. Buoyed by the X-ray laser or "R" program at the Lawrence Livermore National Laboratory (LLNL) [2], EBIT development was carried out by Mort Levine from the Lawrence Berkeley Laboratory (LBL) and Ross Marrs from Livermore (Fig. 1). Funding for EBIT was also received from LLNL's Laboratory Directed Research and Development (LDRD) program — the EBIT project was one of the first, and, I would say, the most successful LDRD project.

As EBIT began to take shape and the electron gun was in place, monitoring the X-ray signal using a solid-state detector was part of the check-out procedure. The biggest question was

Fig. 1. Mort Levine (left) and Ross Marrs at EBIT in Summer 1987. Reprinted with permission of the Lawrence Livermore National Laboratory.

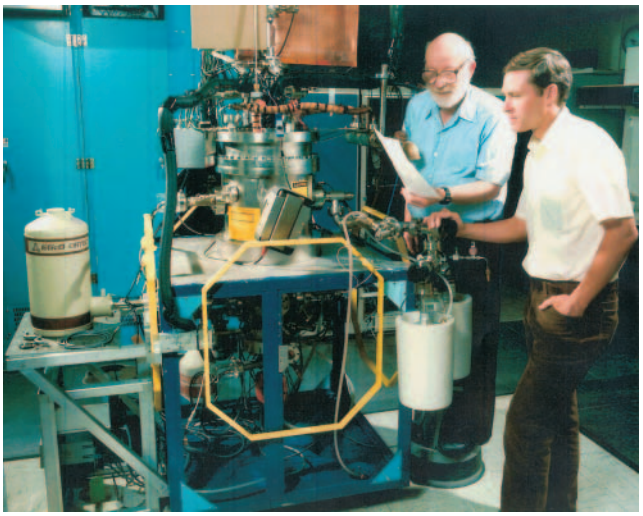

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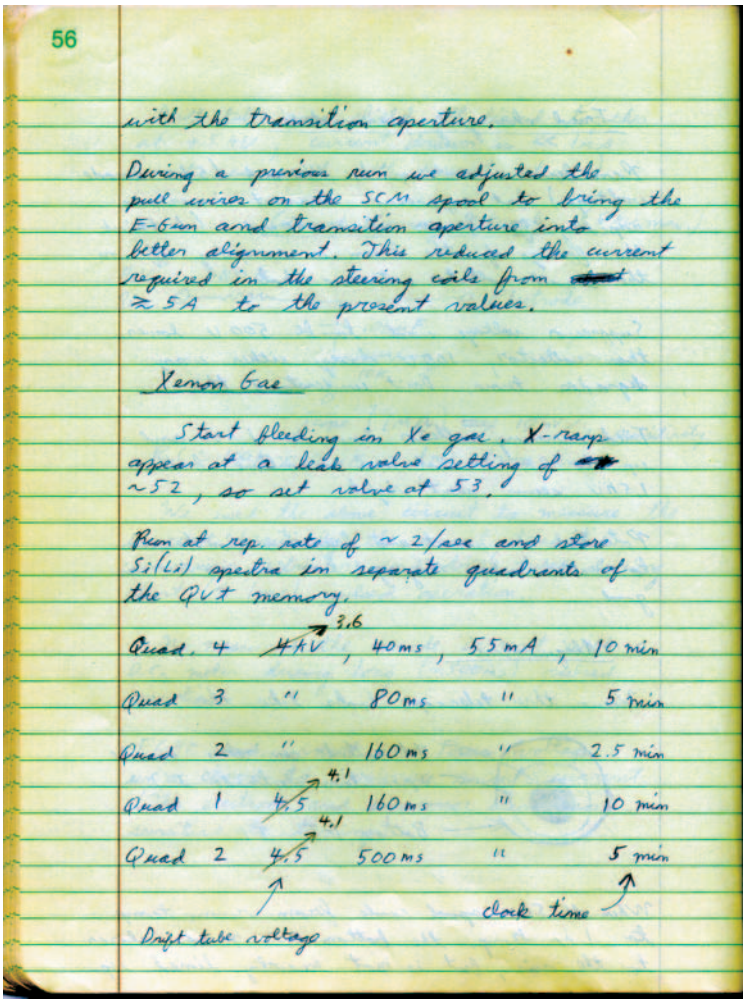
Fig. 2. EBIT notebook entries from 29 October 1986. Xenon spectra monitored with a Si(Li) detector for two different electron beam energies were recorded. The corresponding spectra are shown in Fig. 3.



whether the background emission was low enough, or, conversely, the signal from the ions high enough, to detect signals from highly charged ions. The defining moment came on 29 October 1986, when xenon injection produced X-rays distinctly different from those seen before, as indicated by the notebook entry by Ross Marrs shown in Fig. 2. From that moment on it became clear that EBIT would be able to produce X-ray emission from highly charged ions at will.

Figure 3 reproduces those first X-ray spectra from xenon. The spectra clearly show the typical $3 \rightarrow 2$ emission from xenon. This initial investigation immediately unveiled the existence of dielectronic recombination photons. The beam energies chosen for the measurements, 3.6 and 4.1 keV, were too low to directly excite the observed lines. The lines seen at 4.1 keV are produced by a dielectronic recombination resonance. Few such resonances exist at 3.6 keV, and essentially no X-ray emission is seen, as illustrated in Fig. 3.

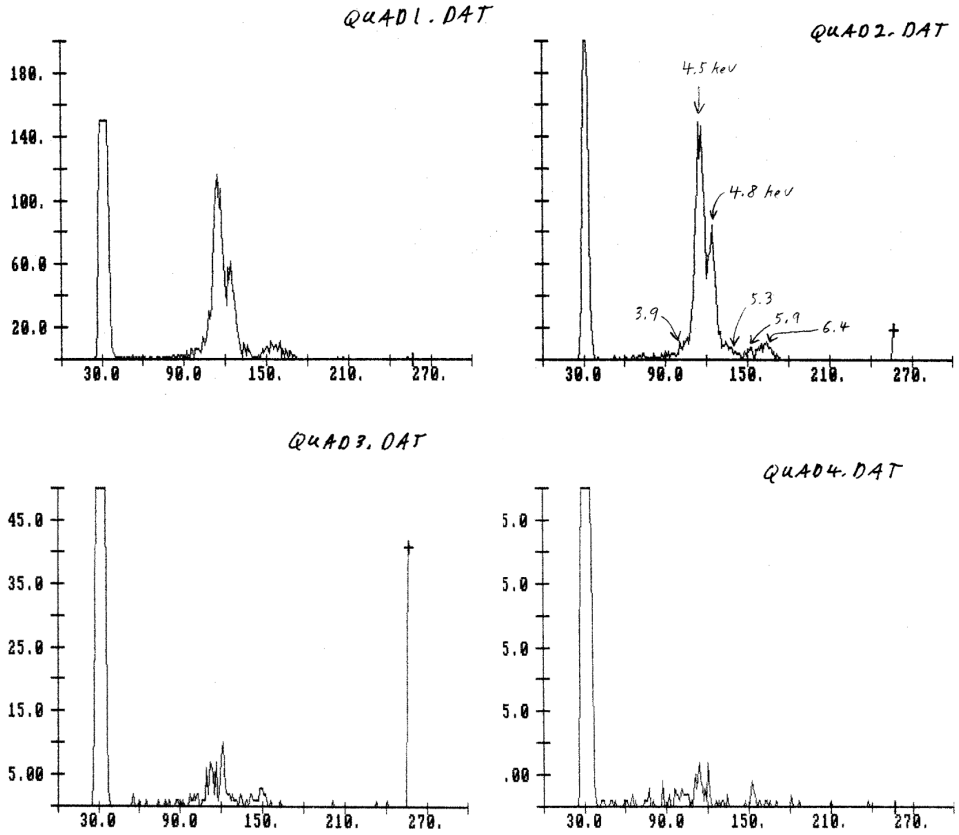
Two weeks later, 10 November 1986, marked the beginning of "routine" spectroscopy on EBIT (Figs. 4 and 5). The construction phase had hardly ended, and the investigation of the X-ray spectra of neonlike xenon and "crudium" began in earnest. Crudium, as described in the log-book entry from that day (Fig. 4), was later determined to be barium and tungsten — elements given off by the electron gun. Since then, crudium has become the standard background in most electron beam ion traps.

The first spectrum that day was labeled "EB010001.D". It simply recorded X-rays from an ^{55}Fe calibration source, as illustrated in Fig. 4. In this notation "EB01" refers to the first ("01") data set from EBIT ("EB"), and "0001" refers to the number of the data file. This $8+1$ labelling convention for data files collected with the CAMAC-based data acquisition system was kept until EBIT was shutdown on 27 September 1991, to make way for SuperEBIT. The last data file that day was labeled EB380411.D.

SuperEBIT (Fig. 6), the high-energy version of the original EBIT, started its first run with file SE010001.D in January 1992, and high-voltage operation was achieved in April that year. The second electron beam ion trap at Livermore, EBIT-II ("EBIT-Two"), was built while EBIT was still running and put into operation before EBIT was to be shut down. It started its operation in January 1990 with file EC010001.D.

The building in which SuperEBIT and EBIT-II were located, building B212, was to be vacated at the end of 2000. As a result, SuperEBIT was shut down on 4 September 2000, and moved to its new location in building B194 within LLNL and EBIT-II

Fig. 3. The four spectra corresponding to the EBIT notebook entries from 29 October 1986. Xenon emission is observed in the top two spectra at a beam energy of 4.1 keV and is produced by dielectronic recombination. Essentially, no such emission is seen in the bottom two spectra recorded at a beam energy of 3.6 keV.



had its last run (Fig. 7) on 17 October 2000. A month later it was moved to LBL, where it carries on an existence as an ion source [3].

At its new location, SuperEBIT was reconfigured into the original EBIT (Figs. 8 and 9), and the first spectrum was taken on 10 April 2001. The high-voltage capabilities of SuperEBIT were reinstalled in 2003, and the machine can now be operated as either EBIT or SuperEBIT, depending on the needs of a given experiment (Fig. 10).

Following the successful operation of EBIT, EBIT-II, and SuperEBIT, electron beam ion traps were constructed outside Livermore. The first two were built at Oxford, England [4], using the Livermore designs of EBIT-II. However, some changes were made. One of these machines was delivered to the National Institute of Standards in Gaithersburg, Maryland [5]. A close copy of EBIT-II was built in the United States and delivered to the Max-Planck-Institute for Plasma Physics at the Humboldt-University in Berlin [6]. Higher energy machines were built at the University of Electro-Communications, Tokyo, and at the Albert-Ludwigs-Universität Freiburg, Germany (since moved to Heidelberg) [7]. More recently, electron beam ion traps were built or installed at Dresden, Shanghai, Vancouver, Stockholm, and Belfast [8], and probably more will come. Not all of these machines have been designed for spectroscopy.

Because many of the new electron beam ion traps have used the word "EBIT", we now refer to the original EBIT electron beam ion trap as EBIT-I ("EBIT-One") to avoid confusion, and to recognize it as the original electron beam ion trap.

3. Spectroscopic instrumentation and measurements

Originally EBIT-I was designed as an X-ray source, therefore, early spectroscopic instrumentation centered on analyzing the X-ray emission with broad-band germanium detectors and flat-crystal spectrometers. This allowed the first measurement of electron-impact excitation cross sections of a highly charged ion [9], followed by the first measurements of dielectronic recombination resonance strengths [10] and resonance excitation cross sections [11].

When compared to other X-ray sources at the time, for example, tokamaks, beam-foil setups at heavy-ion accelerators, vacuum sparks, or laser-produced plasmas, EBIT was a relatively weak X-ray source. To collect more photons, focusing X-ray instrumentation was developed [12]. This resulted in high-resolution spectra useful for accurate wavelength determinations and quantum electrodynamics (QED) studies [13], as well as measurements of ionization cross sections [14] and electron-impact excitation cross sections [15]. Moreover, the first measurements of X-ray polarization [16] and relative line intensities were made [17].

Many high-resolution X-ray spectrometers were developed for EBIT-II [18]. The new instruments in turn allowed for many new atomic measurements, such as measurements of level-specific dielectronic recombination resonance strengths [19], identification of magnetic octupole decay [20], searches for line coincidences for X-ray laser applications [21], and the deter-

Fig. 4. EBIT notebook entries from 10 November 1986. The corresponding calibration spectrum, EB010001.D, and xenon spectrum, EB010006.D, are shown in Fig. 5.

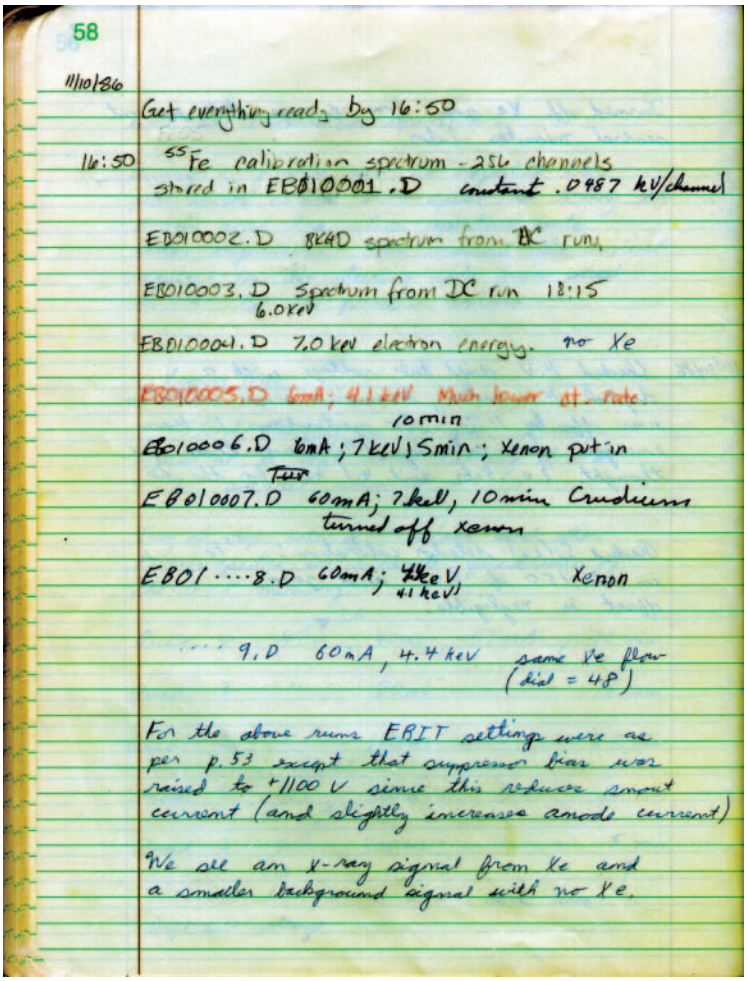
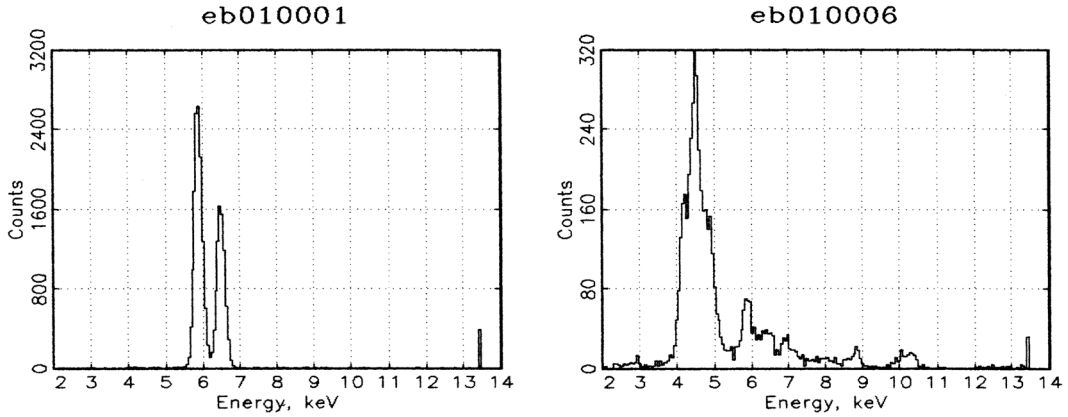


Fig. 5. Spectrum EB010001.D (^{55}Fe calibration) and EB010006.D (xenon) recorded on 10 November 1986.



mination of radiative branching ratios [22]. A crystal spectrometer with resolving power of $\lambda/\Delta\lambda = 68\,000$ was employed to determine the ion temperature and measure the femtosecond radiative lifetime of an excited level in a highly charged ion [23]. In addition, absolutely calibrated monolithic crystals were implemented to make QED measurements of hydrogenic ions [24].

Multiple new flat crystal spectrometers were built, including those that covered extended wavelength ranges. These were mainly used for pioneering work in laboratory astrophysics [25]. Particular focus was placed on the Fe L-shell spectrum — studies of electron-impact excitation, dielectronic recombination, resonance excitation, and line identification were performed for iron [26]. The development of grating spectrometers

Fig. 6. SuperEBIT in B212 in the early 1990s.

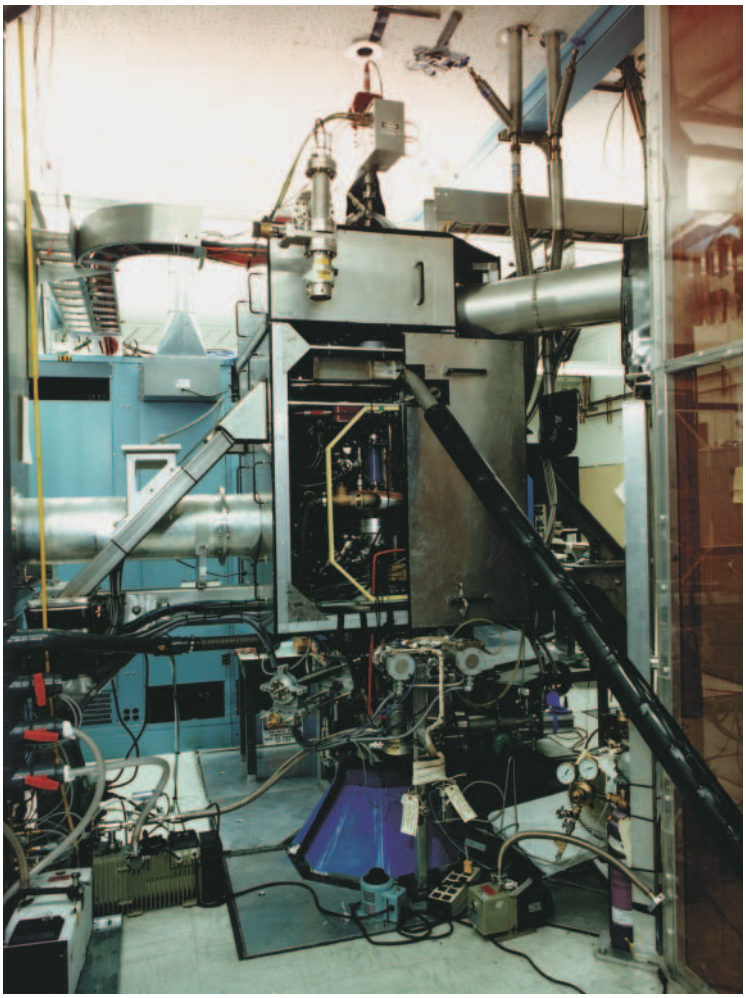


Fig. 7. View of EBIT-II in B212 before shutdown in October 2000. The picture was taken from the former location of SuperEBIT.

for the extreme ultraviolet region yielded additional tools for laboratory astrophysics [27] and allowed extensive studies of the spectra of many astrophysically relevant ions. Optical and ultraviolet spectrometers added additional information for mag-

Fig. 8. New location of EBIT-I in B194 on 12 April 2001.

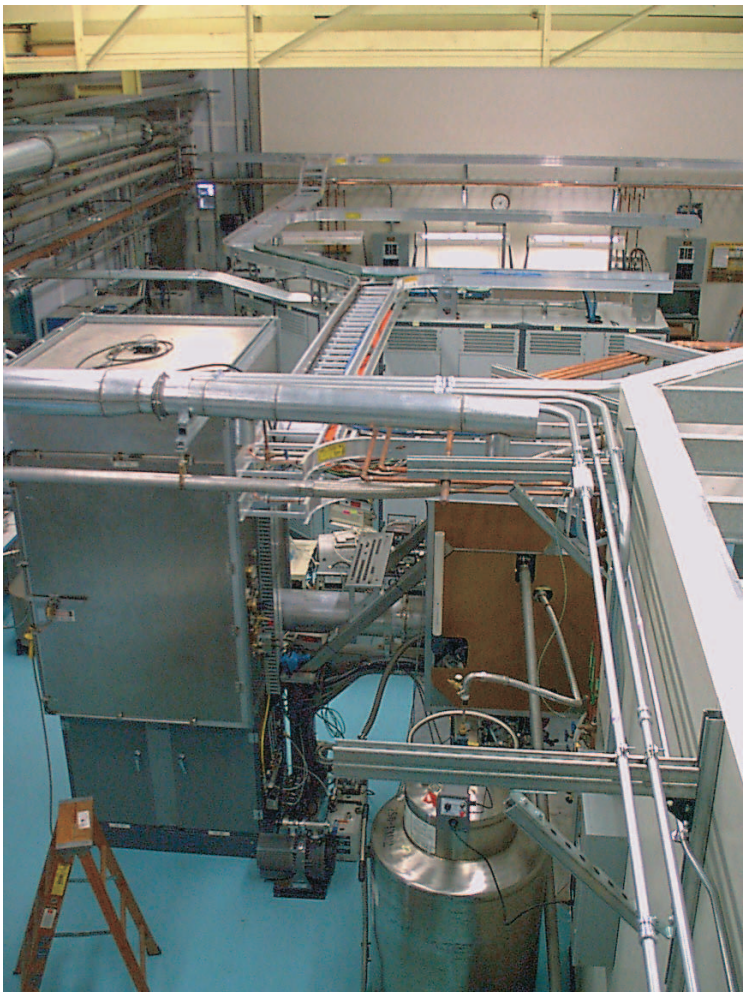
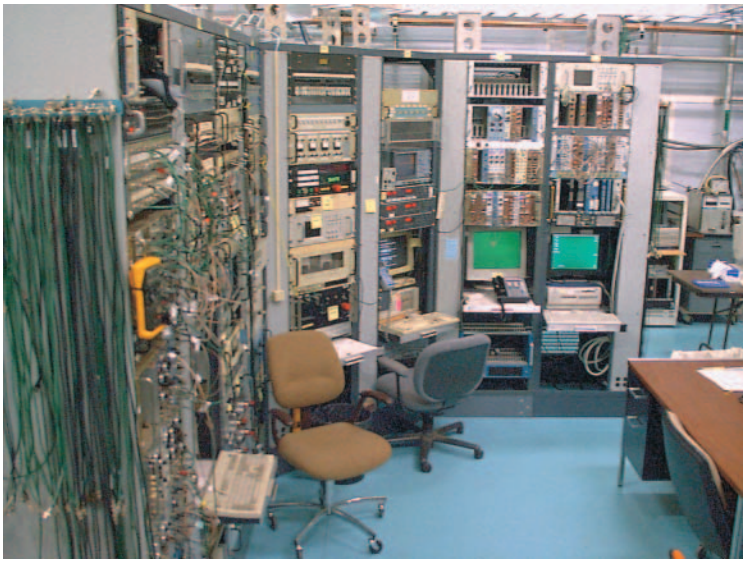
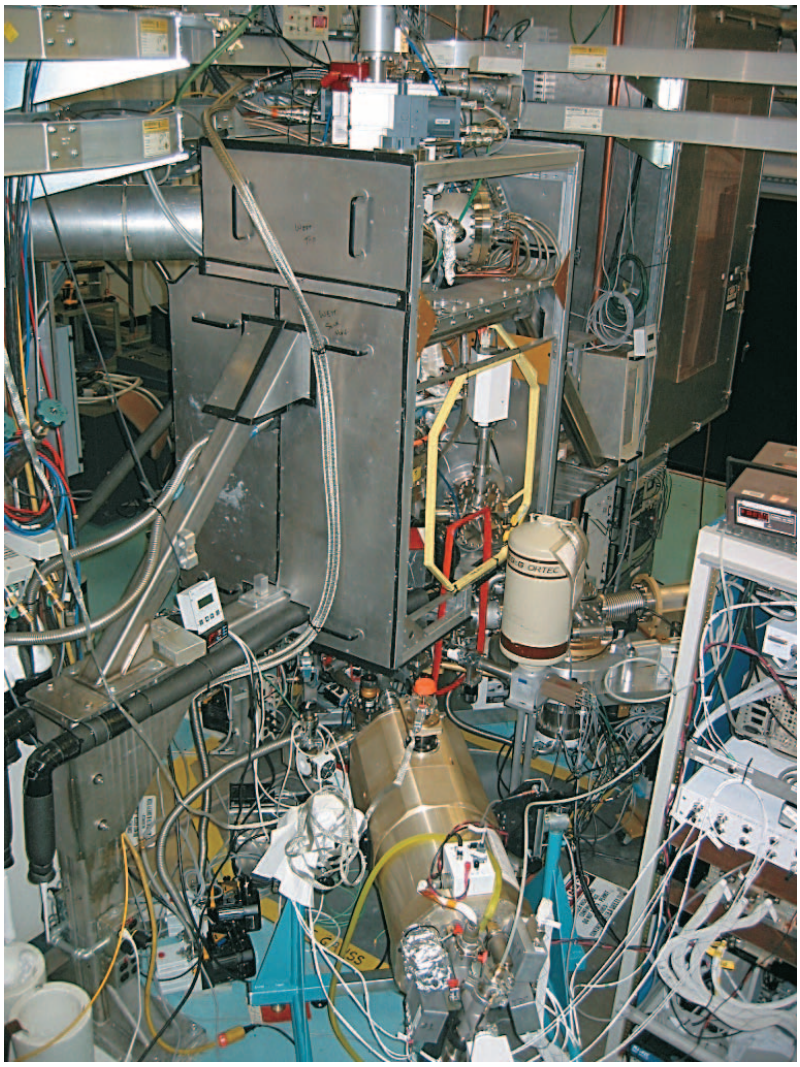


Fig. 9. EBIT-I control room of in B194 on 12 April 2001.



netic fusion [28]. In fact, several of these spectrometers have now found new uses at magnetic fusion facilities — the Alcator tokamak at MIT, the National Spherical Torus Experiment (NSTX) at Princeton, the Compact Toroid Injection Experiment at UC Davis, and the Sustained Spheromak Physics Experiment (SSPX) at Livermore [29].

Fig. 10. SuperEBIT in B194 (November 2003). The microcalorimeter is shown in the foreground.



Fast-switching of the electron beam made possible the first measurement of the radiative lifetime of electric-dipole forbidden X-ray transitions in highly charged ions in the microsecond regime [30]. Development of the magnetic trapping mode, in which EBIT-II was operated without an electron beam, extended radiative lifetime measurements to electric-dipole forbidden optical and X-ray transitions in many other highly charged ions [31]. Fast-switching of the electron beam was also used to develop an operating mode where the electron beam sweeps out a quasi-Maxwellian electron energy distribution [32]. This enabled the production of coronal ionization equilibrium of gold ions at an equivalent plasma temperature 2.5 keV [33].

In 2000, the 36-pixel array X-ray microcalorimeter developed by the Goddard Space Flight Center for the ASTRO-E space mission was added to the suite of X-ray instrumentation of EBIT-II [34]. It provided broadband X-ray detection capabilities coupled with a 10 eV spectral resolution, replacing, in effect, the original solid-state detectors used on EBIT-I since the beginning. The microcalorimeter and its more recent upgrades [35] have been used for various laboratory X-ray astrophysics measurements, as well as measurements in support of high-energy density and nuclear physics [36].

SuperEBIT was designed for electron beam energies as high as 250 keV [37], and energies in excess of 200 keV were indeed achieved. With it, any ion of essentially any element could be produced, including bare uranium, U^{92+}. In other words, SuperEBIT allowed the production of highly charged ions that were heretofore only accessible with a select few heavy-ion accelerators. The highest charge state produced by SuperEBIT to date is heliumlike Cf^{96+} [38]. No other ion trap has so far matched the high charge states produced in SuperEBIT. Because the ions were at rest in SuperEBIT (ignoring the small thermal motion of the ions), spectroscopic measurements were greatly simplified compared to similar measurements on accelerators. Moreover, measurements could be made, such as those of electron-impact excitation, that were impossible to accomplish on accelerators.

X-ray studies on SuperEBIT included determinations of the $2s$ Lamb shift in lithiumlike thorium and uranium [39], and measurements of the variation of the nuclear radii of ^{233}U, ^{235}U, and ^{233}U [40]. In 1998 these studies culminated in the

most accurate QED measurement of any highly charged ion up to that time [41]. As theory developed further, this measurement, involving Bi^{80+}, was shown to be accurate enough to be sensitive to the two-loop self-energy contribution [42]. Dielectronic recombination measurements performed on U^{90+} and neighboring ions provided the first experimental evidence of the quantum mechanical interference between dielectronic recombination and radiative recombination [43]. Production of bare uranium allowed the first accurate measurement of the K-shell ionization cross section of U^{91+} [44].

Optical spectroscopy on SuperEBIT enabled the most precise 1*s* hyperfine structure measurement [45]. In fact, there are now five 1*s* hyperfine structure measurements made with SuperEBIT [45, 46], as well as the only such measurement of the 2*s* hyperfine structure [41]. These measurements probe deeply into the collective behavior of the constituent particles of the nucleus.

Extreme ultraviolet spectroscopy has been developed in recent years on SuperEBIT to include very high-resolution instrumentation [47]. As a result, the accuracy with which QED can be tested has further improved. The recent measurement of the 2*s* two-loop Lamb shift in U^{89+} replaces the earlier measurement of Bi^{80+} as the most accurate bound-state QED test in the strong field of a heavy nucleus [48]. It achieved an accuracy that is equal to the accuracy with which the two-loop Lamb shift at present can be tested in atomic hydrogen.

The magnetic trapping mode, mentioned earlier, was developed on SuperEBIT using ion cyclotron resonance spectroscopy [49]. The Fourier transform ion cyclotron resonance spectrum of Cs^{53+} measured on SuperEBIT still holds the record for being produced by the highest charged atomic ion observed using this technique [50]. On SuperEBIT, the magnetic mode was used to study the X-ray emission from very highly charged ions produced by charge exchange recombination. Using pulsed gas-injection, charge-exchange-induced X-ray spectra were obtained with the magnetic mode for ions as highly charged as heliumlike U^{90+} [51]. Charge-exchange studies on SuperEBIT and EBIT-I using ions of C, N, O, and Ne have proceeded in recent years to provide important information for the development of photon emission models of planetary atmospheres and comets [52].

4. Outlook

The spectroscopy of highly charged ions is a far from complete or yet exhausted science. Highly charged ions provide a window to fundamental aspects of nature and provide a fruitful test bed for the predictions of the Standard Model. Highly precise spectroscopic measurements are basic for understanding QED in strong electric and magnetic fields, for unravelling the way nuclear fields are generated, and for measuring the effect of the weak interaction on atomic transitions. All of these areas of study are very active, and seminal contributions can be made by continuing to study the radiation of highly charged ions. There is also a great need for continued spectroscopy of highly charged ions in fields that depend upon atomic physics data, such as X-ray astronomy, magnetic fusion, high-energy density physics research, laser fusion, X-ray laser development, and microcircuit fabrication at 135 Å. For example, line lists relevant for analyzing observations with the Chandra and XMM-Netwon X-ray satellites are far from complete and require laboratory work. The advent of the International Tokamak Engineering Reactor (ITER) will place new emphasis on developing the emission of krypton and tungsten ions for diagnostics of core and edge plasma. Moreover, hot hohlraum experiments have generated the need for spectroscopic data of gold ions to interpret the observed emission. Furthermore, a common thread in all of these areas is a keen interest in atomic data that can be used as benchmarks for calculations of the ionization balance, i.e., ionization and recombination cross sections, including a multitude of resonant processes. Further detail of these needs is given by the many papers published in this special issue of the *Canadian Journal of Physics*.

Fig. 11. EBIT lead technician Dan Nelson standing next to EBIT-II in B212. Reprinted with permission of the Lawrence Livermore National Laboratory.

Progress in the spectroscopy of highly charged ions can be made by employing advanced techniques for recording the emission from the relevant ions, which go beyond the resolution or sensitivity available earlier. Examples are microcalorimeters, which are poised to yield the first high-resolution spectra at energies above 30 keV [53], and the use of lasers to resonantly excite a particular transition and thus to determine its energy with utmost precision [54]. The available photon energy is greatly increased by the use of free-electron lasers, and by coupling an electron beam ion trap to one of the new free-electron laser facilities. This promises to push the precision associated with optical lasers into the X-ray regime [55].

Judging from the amount of work that can be, and needs to be, done, the outlook for spectroscopy based on the use of electron beam ion traps is very positive. The next 20 years will undoubtedly be very exciting.

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